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Improvements to the Witness Pack Analysis System (WPAS)

Increasing the Accuracy of Hole Area

Y. Baillargeon
M. Szymczak

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Defence Research Establishment, Valcartier

Technical Memorandum

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Authors

Y. Baillargeon and M. Szymczak

Approved by

R. Delagrave

Head, Weapons Effects Section

Approved for release by

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Abstract

The recording, analysis and characterisation of Behind-Armour (BA) debris are of major concern for the defence research community. In order to quickly and efficiently analyse witness packs, the Defence Research Establishment Valcartier has been developing over the past few years the WPAS (Witness Pack Analysis System). The main work performed by this system consists of the semi-automated computation of hole count, hole position and hole area assessment from each plate of a witness pack. However, even with the high accuracy in hole area assessment obtained with a high-resolution digital camera, important errors (up to 80 %) appear for small or non-circular holes. This memorandum presents a simple and efficient method of improving hole area assessment of witness plates. This method can be applied to correct the assessment of witness plates already analysed and for future analysis. The method consists in defining of an equation to represent the absolute error based on the hole area, using calibration plate data and applying it to all witness plates. An error inferior to ±10 % is now obtained for all holes ranging from 0.005 to 20 cm^2 in area.

Résumé

L'acquisition, l'analyse et la caractérisation des débris générés derrière le blindage lors d'un impact suscitent un grand intérêt dans la communauté scientifique de la défense. Dans le but d'analyser rapidement et efficacement les débris arrière, le Centre de recherches pour la défense Valcartier (CRDV) a entrepris, il y a quelques années, le développement d'un système d'analyse semi-automatisé de panneaux témoins nommé *'Witness Pack Analysis System'* (WPAS). Le rôle principal de ce système consiste à calculer le nombre, la position et l'aire des trous obtenus par chacune des plaques d'un panneau témoin. Cependant, malgré la grande précision dans le calcul de l'aire des trous obtenue à l'aide d'une caméra numérique à haute résolution, des erreurs importantes surviennent (jusqu'à 80 %) pour les trous de petit diamètre ou de forme non-circulaire. Ce mémorandum propose une méthode simple et efficace pour améliorer la précision du calcul de l'aire des trous. Cette méthode pourra servir à corriger l'aire obtenue à partir des panneaux analysés précédemment et tout calcul futur. Essentiellement, la méthode consiste à définir l'équation de l'erreur en fonction de l'aire du trou étudié en utilisant quelques données obtenues à partir d'une plaque d'étalonnage et à l'appliquer ensuite à l'ensemble des plaques témoins. Les résultats indiquent qu'une erreur inférieure à 10 % est dorénavant possible pour l'ensemble des trous présentant une surface variant entre 0,005 et 20 cm^2.

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Executive summary

Behind-Armour (BA) effects are of major concern in vulnerability/lethality studies. BA debris studies are usually laborious and time-consuming. However, their interest is of prime importance since the BA debris resulting from the perforating action of projectiles can often cause great damage within a vehicle. In order to characterise efficiently the BA debris effects, the scientific community currently uses one of the two following processes: flash radiography or witness packs. This memorandum addresses the second process, for which a metallic witness pack is placed behind the target to record the hole signature generated by the debris produced by a projectile impact event. Aiming at improving the analysis speed, and indirectly BA debris characterisation, a semi-automatic analysis system called the Witness Pack Analysis System (WPAS) was developed at Defence Research Establishment Valcartier (DREV). This system automatically computes the number, position and area of holes located on a witness plate using a high-resolution digital camera.

However, relatively large errors were observed in the area assessment of small holes or non-circular holes. In consideration of the fact that some threats may generate a large number of small fragments (i.e., shaped charges) and that the majority of fragments do not have a perfectly circular shape, it is important to improve the hole area assessment accuracy. Following the analysis of current witness pack data, a method is defined and applied to the WPAS which yields errors inferior to 10 % in hole area computation for holes ranging from 0.005 to 20 cm^2 in area. Finally, the results obtained from witness plates analysed in the past could be quickly modified using a correction equation, as defined in this memorandum. As a consequence, a better characterisation of BA effects will be possible, allowing an improvement in modeling, prediction and eventually, in vulnerability/lethality studies.

Baillargeon, Y. and Szymczak, M. (September 2001). Improvements to the Witness Pack Analysis System (WPAS) Increasing the Accuracy of Hole Area. DREV-TM-2000-208. Defence Research Establishment Valcartier.

Sommaire

Les effets derrière le blindage sont d'une importance majeure dans les études de vulnérabilité/létalité. Les études concernant les débris générés derrière la cible sont souvent laborieuses et nécessitent beaucoup de temps. Cependant, elles méritent une attention particulière, puisque la formation de débris derrière la cible à la suite de l'impact du projectile, peut causer des dommages importants à l'intérieur d'un véhicule. Afin de caractériser efficacement les débris derrière le blindage, la communauté scientifique utilise généralement l'un des deux procédés suivants: la radiographie éclair ou l'utilisation de panneaux témoins. Ce mémorandum aborde le second procédé, c'est-à-dire l'utilisation de panneaux témoins composés de plusieurs feuilles d'aluminium et d'acier placés derrière une cible pour enregistrer la signature des trous produits par l'ensemble des débris suite à l'impact d'un projectile. Dans le but d'améliorer la rapidité d'analyse et, par le fait même, de caractérisation des débris arrière, un système semi-automatisé d'analyse de plaques témoins "Witness Pack Analysis System" (WPAS) a été mis au point au Centre de recherches pour la défense Valcartier (CRDV). Ce système permet de calculer automatiquement, à l'aide d'une caméra numérique à haute résolution, le nombre, la position et l'aire des trous sur une plaque témoin.

Cependant, des erreurs importantes ont été observées dans le calcul de l'aire des trous de petite taille ou de forme non-circulaire. Puisque certaines menaces génèrent des fragments de très petite taille et en grand nombre (p. ex. les charges creuses) et que les fragments ont rarement une forme parfaitement circulaire, il devient important d'améliorer la précision de l'évaluation de l'aire des trous. À la suite d'une étude des résultats obtenus lors d'essais antérieurs, on a défini une méthode afin d'obtenir une erreur inférieure à 10 % sur le calcul de l'aire des trous ayant une superficie variant de 0,005 à 20 cm^2. Finalement, les résultats de panneaux déjà analysés pourront être rapidement modifiés simplement en appliquant l'équation de correction présentée dans ce mémorandum. Par conséquent, une meilleure caractérisation des effets arrière sera possible, ce qui permettra d'améliorer la modélisation, la prédiction et éventuellement les études de vulnérabilité/létalité.

Baillargeon, Y. Szymczak, M. (September 2001). Improvements to the Witness Pack Analysis System (WPAS) Increasing the Accuracy of Hole Area. DREV-TM-2000-208. Defence Research Establishment Valcartier.

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1. Introduction

When a kinetic (KE) or chemical energy (CE) projectile impacts a target, the BA debris generated inside the vehicle affects its vulnerability. Witness packs are conveniently used to record BA debris due to their simplicity, low cost and easy installation. When experimental tests are conducted, a four- or seven-plate metallic witness pack (steel and aluminium) is used behind the target to record the debris, as stipulated in STANAG 4190 [1]. This method may be more appropriate than flash radiography in some cases such as when the number of fragments generated becomes considerable. However, when the number of fragments becomes important, the witness pack analysis may become time-consuming: the area and position of each hole on each witness plate having to be defined. To avoid this heavy constraint, a semi-automatic system, the Witness Pack Analysis System (WPAS) was developed at DREV under contract by IMAGO Machine Vision Inc. [2]. The process consists in placing each individual witness plate, perforated by BA debris, on a light table, grabbing the plate image with a high resolution digital camera and computing the number, the area and the centroid position of each hole with the WPAS software. The output file created is then used by the Debris Characterisation and Modeling (DeCaM) software package to compute the mass, velocity and trajectory of each fragment [3]. In this software, the area of the holes within each plate is used to assess the mass of the fragments, whereas the number of plates perforated in the witness pack yield information about the fragment's minimal kinetic energy. With the kinetic energy and the mass, the fragment velocity will be computed. It is therefore important to obtain an accurate estimate of the hole area since other values are a function of this computed value.

A study of the WPAS output revealed that the accuracy for very small holes and non-circular holes could be relatively low, up to 80 % in error. It was observed that for circular holes, the error increased with decreasing hole area. Once this fact was known, work has been carried out to increase the accuracy of the WPAS.

This memorandum presents a brief review of the theory related to image acquisition, followed by the method used to improve its accuracy and finally, the associated results and analysis.

This study was performed at DREV's 'Behind-Armour Effects Studies Laboratory'. This work was carried out between April and August 2000 under unit 12FH12 'Behind-Amour Effects Characterisation and Prediction'.

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2. Background

The characterisation of BA debris can be performed with hardware and software like that of the WPAS to reduce the time required to acquire the information from witness packs. Witness packs contain information about the position and area of each fragment hole. The process of acquiring and recording this data may be time-consuming. The holes themselves can be easily identified, but their centroid and area can sometimes be very difficult to obtain, depending on the shape of the hole. Therefore, the semi-automatic system, WPAS, described below was seen as an efficient way to improve speed and accuracy when BA debris information is required.

2.1 WPAS

The first step in obtaining reliable and accurate mass, velocity and trajectory values of BA debris is to acquire the data with the most reliability. Metallic witness packs are therefore placed behind the target [1] to record the signature left by the perforating fragments. The witness packs can have dimensions of either 2 ft x 2 ft (61 cm x 61 cm), 3 ft x 3 ft (91 cm x 91 cm) or 4 ft x 4 ft (122 cm x 122 cm). The smaller is used for small calibre projectiles, the 3 ft x 3 ft for medium calibre ammunition tests under laboratory conditions and the large 4 ft x 4 ft pack is used for full-scale field tests. The witness packs, which are comprised of multiple plates, are then dismantled and each plate is placed on a light table and scanned by a high-resolution digital camera (Kodak Megaplus model 1.4i) which is controlled by the Witness Pack Analysis System. The WPAS then labels the holes and calculates the corresponding centroid position and area. Once these basic calculations are obtained, the fragment trajectory, mass and velocity are computed with the DeCaM software package.

2.2 System Components and Settings

The WPAS consists of a PC type computer, a high-resolution digital camera (Kodak Megaplus model 1.4i) and its controller. The camera resolution is $1317_{(H)}x1035_{(V)}$ pixels (i.e. 1317 pixels in the horizontal plane and 1035 pixels in the vertical plane) but the acquisition card in the system only allows a 1024x1024 pixel resolution. Therefore, the second resolution is used to grab images.

The PC includes a software where the threshold and the "Look-Up-Table" LUT values are specified (their effect will be explained further in this document). This software acquires the image from the camera which is affected by the controller settings. The most important parameter on the controller is the gain value. Other parameters affecting the images are on the camera: focus, camera aperture and the lens. The distance between the camera and the light table needs to be fixed once the focus is adjusted.

All the work was completed at DREV using a 2 ft x 2 ft and a 4 ft x 4 ft light table. In both cases, the gain was set to zero, the black level was fixed, the control mode was used, the shutter was turned on, and finally, the exposure time was set to 50 ms on the controller. Also,

the light in the room was always turned off in order to obtain a higher contrast and the focus on the camera was always set to infinite for all the trials.

With the 2 ft x 2 ft light table, a 20-mm lens was used for the camera, the camera aperture was set to 11 and the distance between the camera and the witness plate was 199 cm. However, with the 4 ft x 4 ft a 24-mm lens was used for the camera, the camera aperture was set to 16 and the distance between the camera and the witness plate was 477 cm. The table being twice larger than the 2 ft x 2 ft, the number of pixels for a hole was four times smaller.

The results in this memorandum were obtained for a specific set-up of the digital camera. The focus, the camera aperture, the gain, the physical position of materials and the light in the room will produce different results even if the threshold and the LUT values used were the same. The light table was perpendicular to the camera line of sight and the camera was centred with the centre of the witness plate. The camera is aligned using a mirror since a slight deviation of the camera angle from the perpendicular can significantly change the results.

2.3 Calibration Plate and Light Tables

To determine the accuracy of the system, a calibration plate, having holes of known position, shape and area, is used. Although this plate may not represent witness plates placed behind a target, its use is critical for the analysis. Two calibration plates exist, a 2 ft x 2 ft plate and a 4 ft x 4 ft plate. Both have a basic 1 ft x 1 ft pattern, as shown in Figure 1, which is repeated to generate the entire plates. The hole position, size and area are presented in Table 1. To adequately simulate the wide spectrum of hole shape and size left by debris perforating witness plates, various geometric shapes of different sizes are presented. These forms vary from circular to narrow rectangular shapes and also present groupings of holes. One column of holes was removed from the analysis with the 2 ft x 2 ft light table (column 0) since the frame of the light table used to support the plates covers these holes.

The calibration plate is not identical to the witness plates usually used in the witness pack since the thickness, the shape of the holes and the material of the plate could be different. Also, real witness plates will often reveal petaling around the holes. In general, the larger the hole, the greater the petaling effect around the hole. The effect of these different parameters on the area assessment was not studied and should be eventually investigated.

The light tables present four (4) reference holes, one at each corner, used to define the relationship between the coordinate system used by the computer and the real world coordinate. The area beneath the plates is illuminated by electric fluorescent tubes yielding an image having white holes on a black background. An opaque translucent polyethylene plate covers the tubes to uniformly diffuse the light. The table is painted black in order to avoid any light reflection.

2.4 Procedure for Data Acquisition

The procedure is quite simple and rapidly executed. The first step is to calibrate the light intensity by first capturing an image of a blank light table (i.e. lights on without plate). Once this image is grabbed, the analysis of plates can begin. The calibration plate is the first plate to

be scanned in order to obtain information about the accuracy of the system. According to the black intensity level and the blank table intensity, the pixel's intensity is normalised (from 0 to 255). The pixels having an intensity lower than the threshold value are rejected and then, the normalised image can be used to calculate the absolute error of hole area where computed areas are compared to the actual calibration plate areas. At this time camera settings can be modified to find the optimal configuration (minimal error and capture of all the holes). Once this is achieved, the witness plates can be analysed. The procedure can be summarised as follows:

1. Turn off room lights,
2. Grab the image of the light table (without plate),
3. Adjust the different parameters of the software, the controller and of the high-resolution digital camera,
4. Grab the image of the calibration plate,
5. Analyse the results for circular hole area with WPAS and if the results are not acceptable go back to step 3,
6. Grab the image of the witness plate,
7. Calculate the number, area, centroid and position of holes with WPAS,
8. Look at the number of holes found and if some holes are not captured by the WPAS return to step 3 because the setting was probably not adequate (unless new defects have been identified for the camera),
9. Place the next witness plate on the light table and come back to step 6 until all the plates are scanned.

Steps 3 and 5 are usually completed only once and the settings are valid for a complete batch of plates.

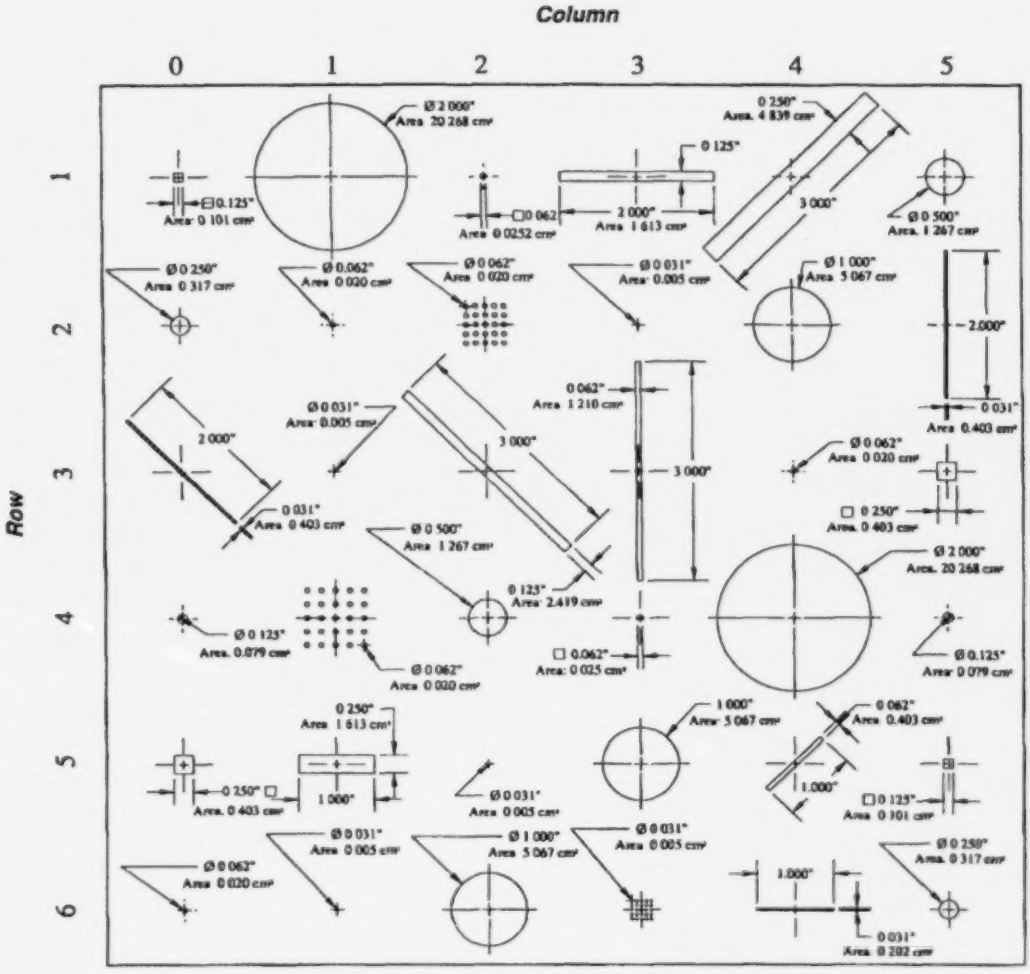

Figure 1. *Basic calibration plate pattern*

Table 1. Basic calibration plate description

HOLE POSITION	DIAMETER		H		W		AREA
(row, column)	*(inches)*	*(cm)*	*(inches)*	*(cm)*	*(inches)*	*(cm)*	*(cm^2)*
(1,0)			0.125	0.318	0.125	0.318	0.101
(1,1)	2.000	5.080					20.268
(1,2)			0.062	0.157	0.062	0.157	0.025
(1,3)			2.000	5.080	0.125	0.318	1.613
(1,4)			3.000	7.620	0.250	0.635	4.839
(1,5)	0.500	1.270					1.267
(2,0)	0.250	0.635					0.317
(2,1)	0.062	0.157					0.020
(2,2)	0.062	0.157					0.020*
(2,3)	0.031	0.079					0.005
(2,4)	1.000	2.540					5.067
(2,5)			2.000	5.080	0.031	0.079	0.403
(3,0)			2.000	5.080	0.031	0.079	0.403
(3,1)	0.031	0.079					0.005
(3,2)			3.000	7.620	0.125	0.318	2.419
(3,3)			3.000	7.620	0.062	0.157	1.210
(3,4)	0.062	0.157					0.020
(3,5)			0.250	0.635	0.250	0.635	0.403
(4,0)	0.125	0.318					0.079
(4,1)	0.062	0.157					0.020*
(4,2)	0.500	1.270					1.267
(4,3)			0.062	0.157	0.062	0.157	0.025
(4,4)	2.000	5.080					20.268
(4,5)	0.125	0.318					0.079
(5,0)			0.250	0.635	0.250	0.635	0.403
(5,1)			0.250	0.635	1.000	2.540	1.613
(5,2)	0.031	0.079					0.005
(5,3)	1.000	2.540					5.067
(5,4)			1.000	2.540	0.062	0.157	0.403
(5,5)			0.125	0.318	0.125	0.318	0.101
(6,0)	0.062	0.157					0.020
(6,1)	0.031	0.079					0.005
(6,2)	1.000	2.540					5.067
(6,3)	0.031	0.079					0.005*
(6,4)			1.000	2.540	0.031	0.079	0.202
(6,5)	0.250	0.635					0.317

*Multiple holes

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3. Theory

When the first version of the WPAS was built, a tool had to be developed to better understand the relevant parameters affecting the resolution capacity of the camera. That is, the image grabbed by the high-resolution digital camera has to be calibrated to yield the closest values of hole centroid position and hole area to the real absolute values.

To improve the area assessment a preliminary analysis of the absolute error as a function of the hole shape was necessary. The absolute error was calculated for each hole using equation 3.1 where the $Area_{measured}$ is the actual area of the holes of the calibration plate and $Area_{computed}$ is that computed by the WPAS:

$$Error_{absolute} = \frac{Area_{computed} - Area_{measured}}{Area_{measured}} \qquad (3.1)$$

Figure 2 presents the absolute error as a function of hole area for circular hole of 5.067cm^2, 1.267 cm^2, 0.317 cm^2, 0.079 cm^2, 0.020 cm^2 and 0.005 cm^2 area. These areas correspond to diameters of 1", 1/2", 1/4", 1/8", 1/16" and 1/32". As illustrated in Figure 2, it appears that the

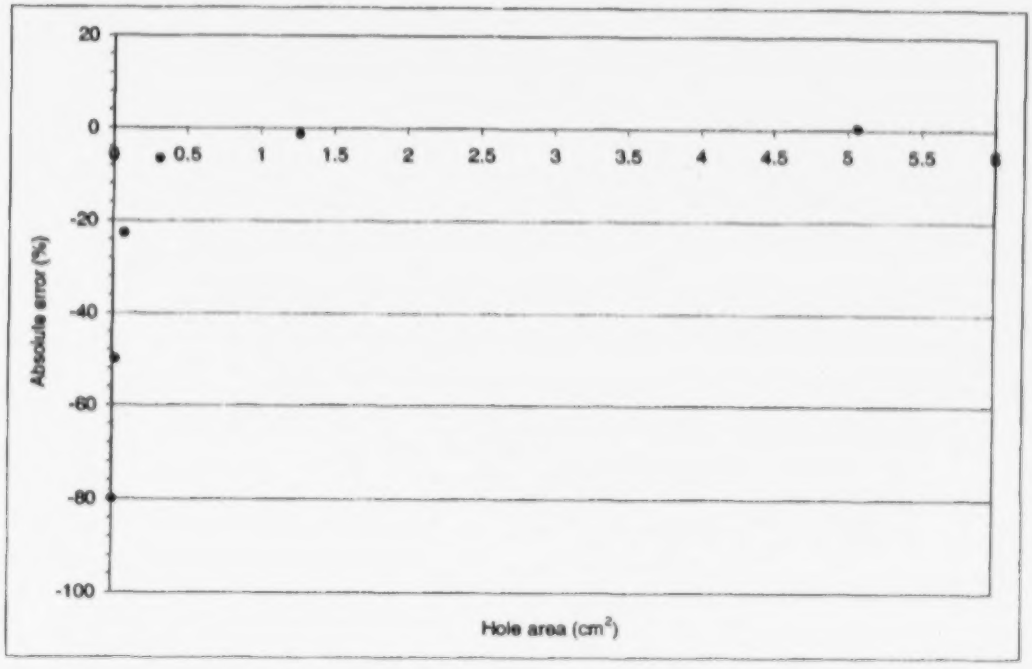

***Figure 2.** Absolute hole area error (%) for circular holes*

error increases drastically for holes with areas inferior to 1 cm^2. It is also important to establish whether this same trend applies to other hole shapes. Figure 3 presents the error as a function of hole area for all holes having a square or circular shape. It can be deduced that hole shape does not have a large effect on the curve shape for a hole ratio of height/width≈1 (h/w). It must be noted that for all the graphs representing the absolute error, the areas obtained from the narrow hole grouping (i.e. 5x5 grid) at position (2,2) and (6,3) (i.e. (row, column)) in Figure 1 are not presented and the reason will be explained further. However, the hole grouping at position (4,1) is included since all the individual holes are visible when the witness plates are analysed.

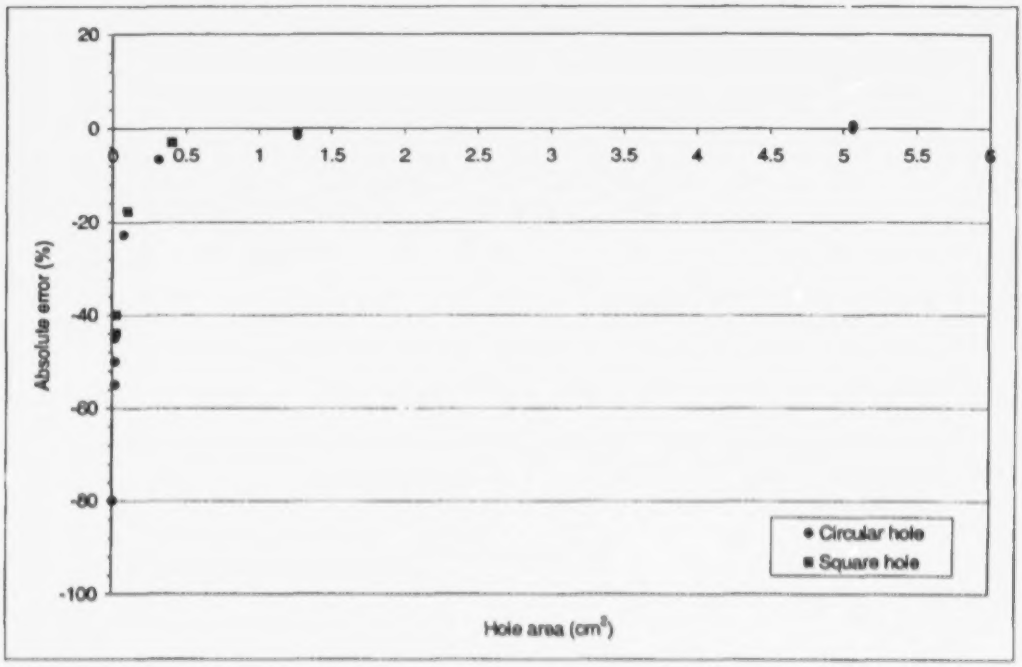

Figure 3. *Absolute error (%) for holes having a ratio h/w=1 (i.e. circles and squares)*

It follows that the absolute error for all the holes of the calibration plate, and consequently of all shapes, is presented in Figure 4. The general trend is similar to that observed for circular and square holes, that is that the error increases as hole area decreases. However, holes with a large h/w ratio have greater errors for areas ranging from 0.202 to 2.419 cm^2. The two largest errors are for holes located at positions (2,5) and (3,3) in Figure 1. The value of their h/w ratio is respectively 48 and 64, representing very narrow rectangles. In fact, all the holes which fall out of the trend have a h/w ratio higher than 15. Therefore, it appears that the largest error is for the smallest holes and for holes of narrow rectangular shapes. To further explain the error in area for the entire hole shape distribution, threshold grey level and light intensity must be understood and considered.

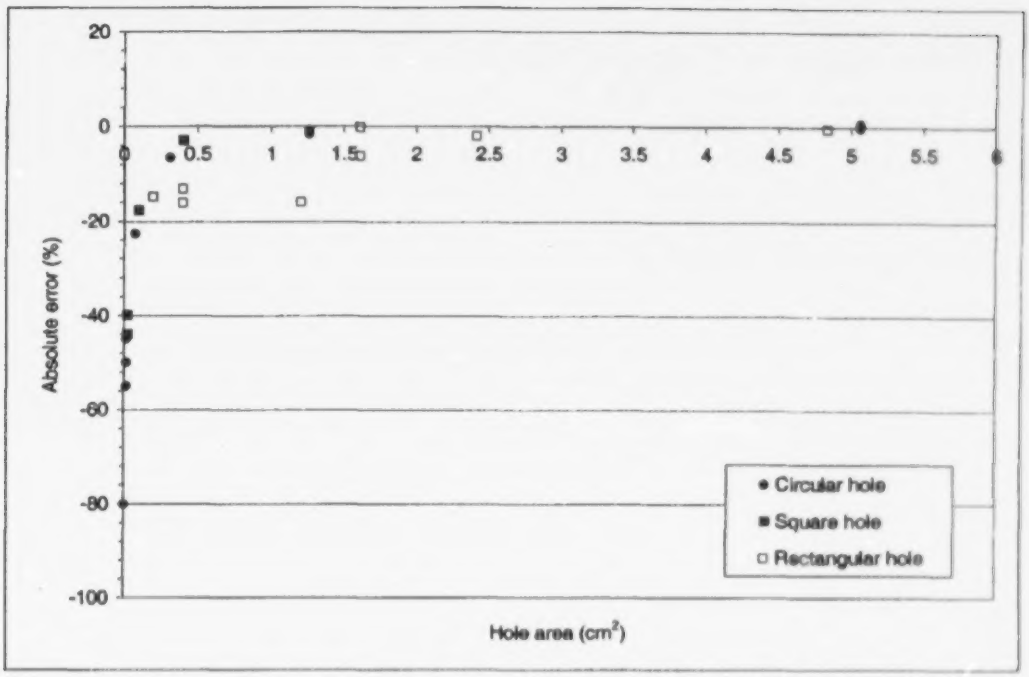

Figure 4. *Absolute error (%) for all the holes of the calibration plate using a threshold value equal to 30*

3.1 Threshold Grey Level

To assess the area of a hole using a digital camera and a light table, an important input value is required by the computer to obtain reliable and accurate data: the threshold grey level. This value (defined in the software) is used to retain all pixels above a defined threshold grey level and to discard all pixels below this same threshold level. This allows the definition of hole boundary. Since the fluorescent light source used within the light table is diffuse, the light intensity will not clearly be white or black, there will be a transition from white to grey and eventually to black. This transition region is caused by the halo present around the hole. Therefore, the closer the boundary is to the real edge, the more accurate should be the hole area.

Figures 5, 6 and 7 present the graphical representation of the calculated hole areas for threshold values of 20, 30 and 40, respectively. It is important to note that the calculated areas are only represented as circles (software limitation). As a consequence, one can first comment on whether or not all holes have been identified. The calibration plate of Figure 1 was scanned for three different threshold values. As can be seen in Figure 5, with the lowest threshold value of 20, all the 25 small holes of the 5x5 grids located in the position (2,2) as well as position (6,3) are considered as only one hole. A threshold value of 20 means that every pixel with an intensity lower than 20 will be considered as background (i.e. black) and every pixel with an Intensity above 20 will be a part of the hole. As mentioned, the 5x5 grid hole was

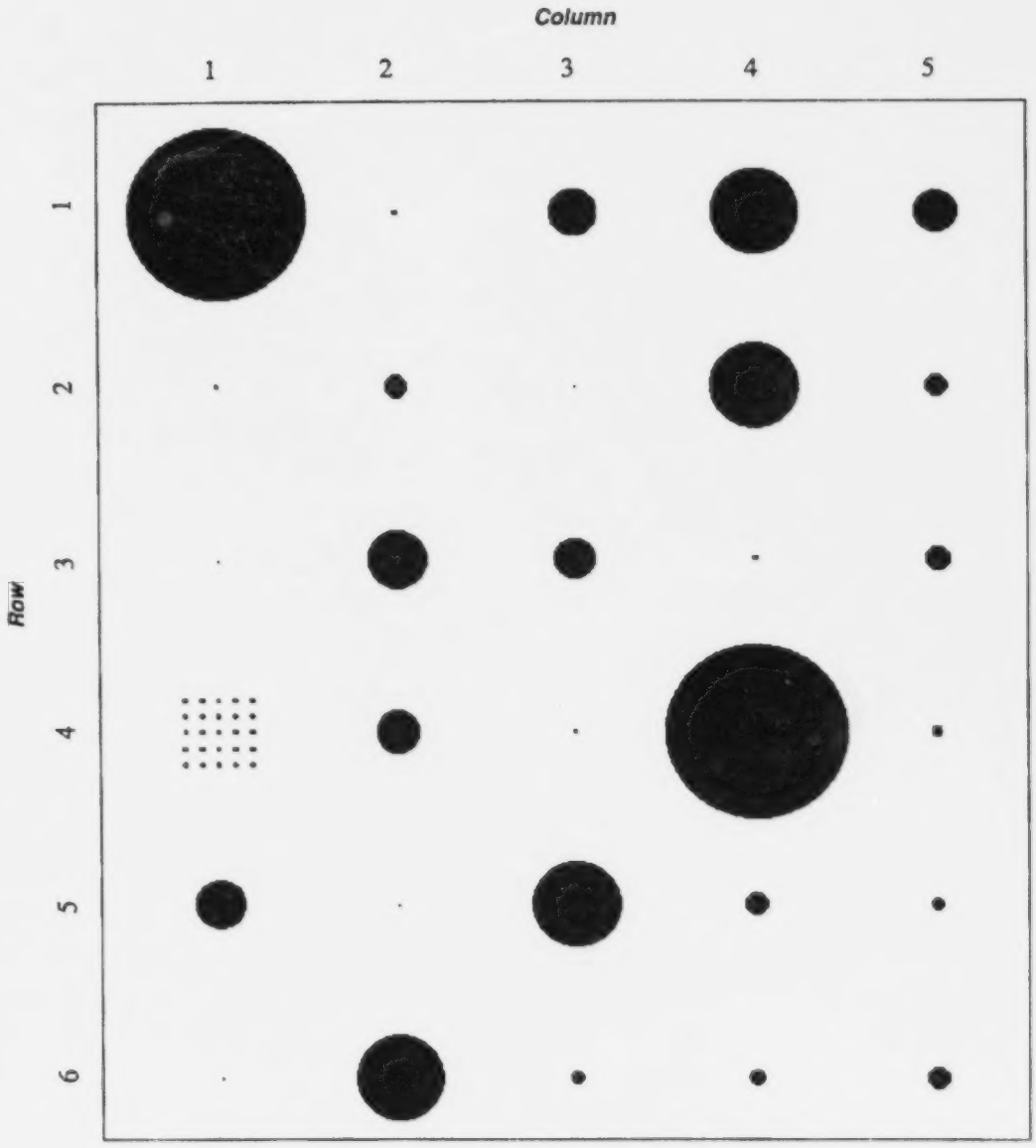

Figure 5. *Picture of the calibration plate using a threshold value = 20*

represented as only one hole. The reason is that the lower threshold causes the holes to be larger than real. The neighbouring holes therefore merge and are considered as one single hole. When the threshold is set to 30, some individual holes of the grid located at position (2,2) begin to appear, whereas the grid at position (6,3) still appears as one object (Figure 6). With a threshold value of 40, all the holes of the grid (2,2) are now present, whereas the grid at position (6,3) still only appears as one object (Figure 7). One can also observe that at this

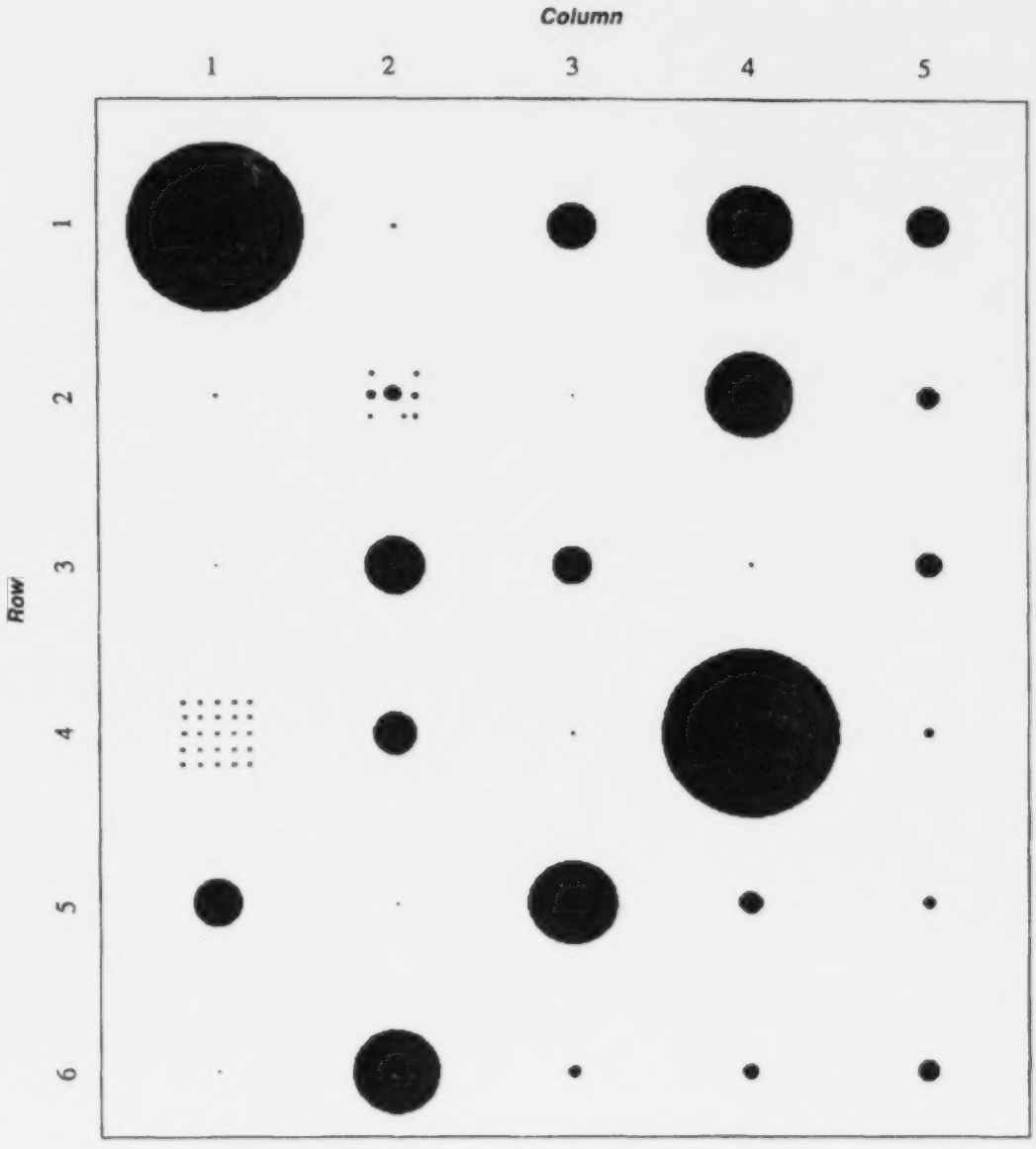

Figure 6. *Picture of the calibration plate using a threshold value = 30*

last setting, four holes at positions (2,3), (3,1), (5,2) and (6,1) have disappeared and are consequently below the threshold value. It follows that to avoid any confusion during interpretation of graphics of the absolute error, the holes located at position (2,2) and (6,3) in Figure 1 will not be considered in the graphics plot. In order to obtain the smaller square box made of 25 distinctive holes located in position (6,3), the threshold value should be increased to a level higher than 40. Therefore, the closer the neighbouring holes, the higher has to be the

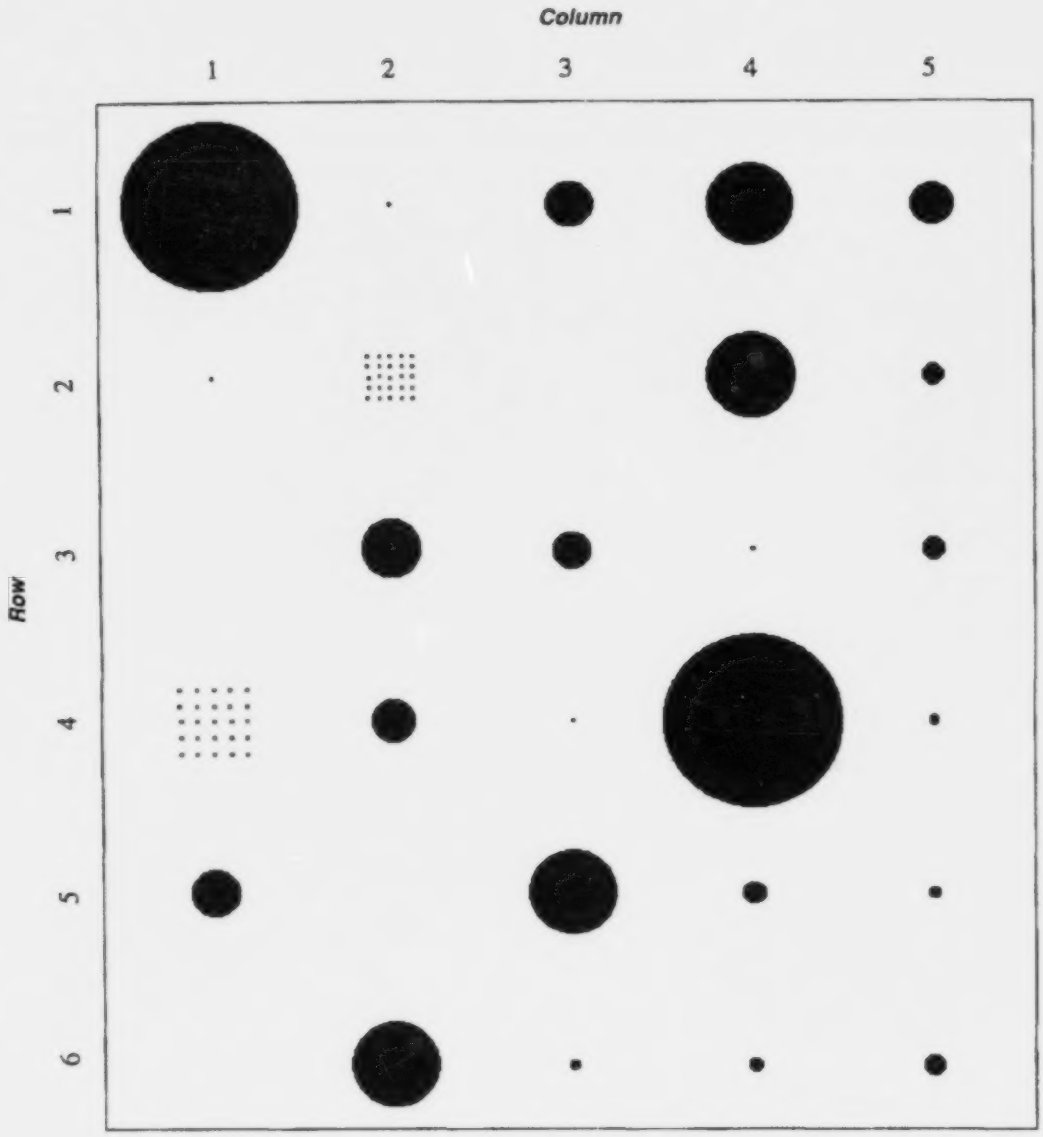

Figure 7. *Picture of the calibration plate using a threshold value = 40*

threshold level to distinguish the holes of a grid. Hence, the threshold level will have to be selected by the user, depending on whether or not small holes and close neighbouring holes are present. A special phenomenon is produced when the threshold value is too high. For the larger holes, the area assessment will become more accurate since the halo will be reduced in size. However, the small holes will now disappear. This is caused by the fact that the light intensity read by the high-resolution digital camera decreases with the size of the holes. This concept is explained in the following section.

3.2 Light Intensity

The software WPAS used both a digitised picture of the witness plate and a blank table image to assess the hole area. The blank table image is used to define the light intensity of each pixel without a witness plate. As a consequence, a pixel is considered as completely inside a hole if its intensity recorded in the witness plate image is the same as that in the blank table image. If it is not the case, then the computer will consider that this pixel is located on the edge of the hole and that only a fraction of this pixel is inside the hole. In this case, the computer will record a fraction of the pixel area. This is the only way to record area of holes smaller than or similar to the size of a pixel without producing a substantial error.

Figure 8 illustrates the fraction of pixel recorded for each one located on the central vertical axis of a circular hole. The holes of 1", 1/2", 1/4" and 1/8" in diameter are respectively of dimensions 37, 19, 9 and 5 pixels wide (1 pixel = 0.027"). However, Figure 8 reveals that the analysis yields a larger number of pixels for each, that is 52, 32, 20 and 14 pixels, respectively. To explain this difference one could look at the ½"Ø hole. This hole is

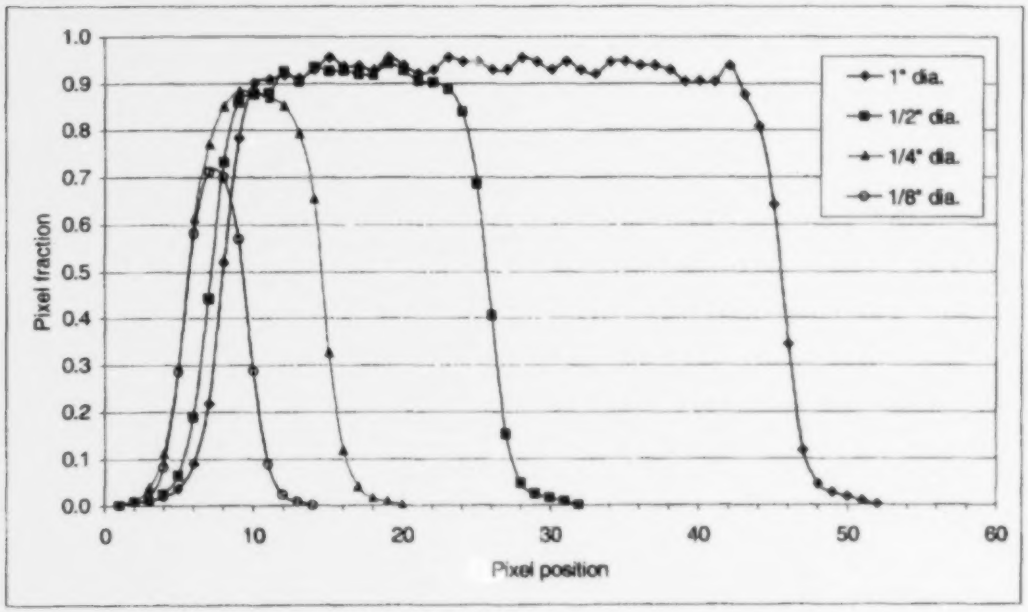

***Figure 8.** Variation in the intensity of pixels through the axis of a circular hole*

comprised of 19 pixels that are from pixel 7 to 26, since the first six (1 to 6) and the last six (27 to 32) pixels were recorded outside the holes. If the light intensity recorded by the camera was constant inside the entire hole, the fraction of pixel record should be constant. However, as seen in Figure 8, as the pixels approach the edge the intensity decreases. The smaller the hole, the larger is the effect of light intensity on the hole area since the number of pixels close to the edge will represent a larger percentage of the entire area. Figure 8 also illustrates a maximum fraction of 0.94 instead of 1 for pixels inside the ½"Ø hole. This is caused by the fact that the pixel intensity decreases with the size of the hole. Figure 9 presents the maximum pixel fraction for the different hole diameters. As can be seen, the graph shows that this

phenomenon seems to be almost constant (a light progression is noted) for holes larger than ½"Ø hole, but for smaller holes a substantial intensity drop appears. This, associated with the decrease in light intensity at the boundary, will cause a reduction in the hole area calculation. As it was shown in Figure 2, for holes smaller than ½"Ø (1.267cm^2), an error is introduced. Finally, Figure 8 illustrates a halo around the ½"Ø hole since the intensity varies from pixel 1 to 7 and from pixel 26 to 32. These halos are around all the holes and allow an increase of the hole area as long as the threshold value is below the border pixel intensity (pixels 7 and 26).

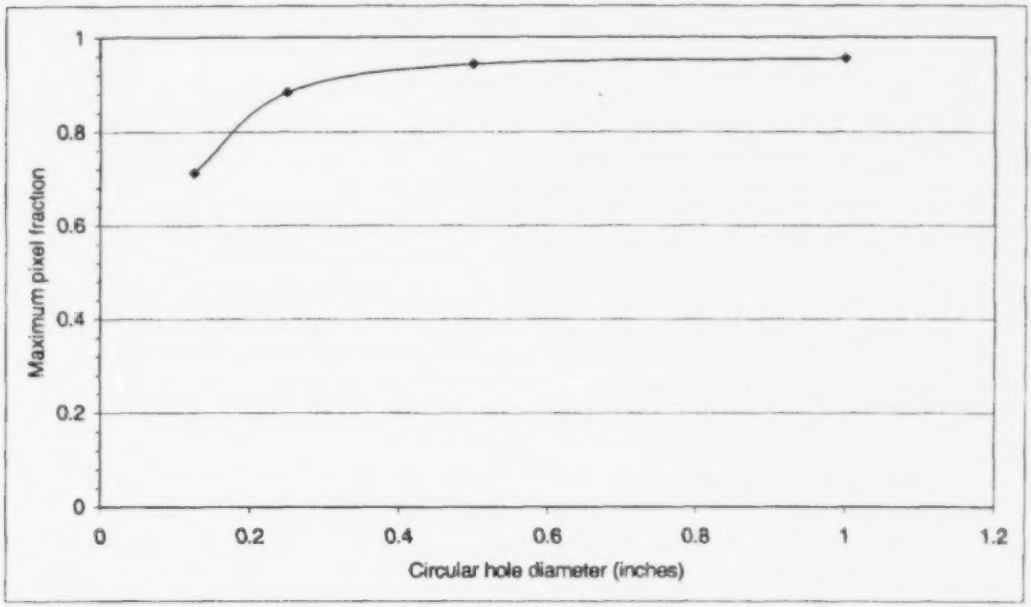

Figure 9. *Maximum value of the fraction of pixel found in a hole*

A hole can be so small that it can be represented by as little as a single pixel without any other hole close to it to increase its intensity over the threshold level. However, if a neighbouring hole is located very near to this one, it will now be possible to increase the intensity over the threshold value due to a cumulative effect. This is why the single holes located in positions (3,1), (2,3), (5,2), (6,1) of Figure 7 are not visible and the hole grouping (5x5 grid) in position (6,3) is visible as one hole for a threshold value of 40. The light diffusion (fluorescent sources diffuse the light compared to laser beam) of the neighbouring holes increases the intensity of each hole of the 5x5 grid. Even if the intensity is not as high as the intensity without a witness plate (i.e. blank table image) the value is higher than the threshold value and the area can be computed. Unfortunately, the single holes of the same diameter are not visible since their intensity is too low.

4. Method

In order to reduce the error in hole area for all the holes using the calibration plate, improvements have to be made for the area computation of small holes. As mentioned previously, the light intensity appears to be a major cause of error. In 1998, work was completed by IMAGO Machine Vision Inc. to improve the computation of hole areas [4]. The approach used was to increase the light intensity for low-intensity pixels (found in small holes and at the edge of each hole) and almost maintain the same intensity level for the high-intensity pixels (found inside larger holes). The value of pixel intensity was increased using a power law equation. The power law equation was affected by a value called "Look-Up-Table" (LUT). This value was used as a variable in the equation to define the level of correction for the intensity according to the pixel intensity.

The method used to further improve hole area computation for results of old tests and the method used to improve hole area for future raw data is described in the following paragraphs.

4.1 Correction on Data Obtained Prior to 1998

Numerous terminal ballistics tests were completed with the use of witness packs prior to 1998 which require hole area corrections. Although many of these witness packs were discarded, the data of each witness plate and calibration plates associated with these tests were carefully archived. With the aim to improve the results of data obtained in the past, a method is necessary to be developed for application to any previous results.

As a consequence, It is required to correct the errors caused by the variation in light intensity across the plates and due to the effect of the threshold value (Figure 10). In the first case, the error in hole area for holes of different shapes (i.e. small and large circular and rectangular) varied, as presented in Figure 4. The absolute error for non-circular shaped holes was always superior or equal to the error of a circular hole of same area independent of the threshold value. It was also observed that the same error trend applied to various threshold value settings but with an increase in error proportional to the threshold value. Therefore, the hole area absolute error could be drastically reduced by an equation which is a function of absolute error and area over the entire range of areas. Equation 4.1 presents a general form of the best-fit which could be applied to circular holes (Figure 10):

$$f(x) = \frac{Ax^C - B}{x^2} \tag{4.1}$$

This general equation was derived from observation of many graphs and using the correct coefficient, this curve will be an excellent fit to the experimental data. The constants A, B and C are the shape factor, the resolution factor and fit constant, respectively. The constant C was found to lie between 1 and 1.5, depending on the threshold used. The three constants can be obtained by solving the equation using different calibration plate results and minimising the sum of squares. Once the constants are defined, the error curve can be obtained. Since the

absolute error is then known for a specific area, this error can be decreased with the new hole area defined by equation 4.2:

$$Area_{corrected} = \frac{Area_{computed}}{(1 + f(x)/100)} \qquad (4.2)$$

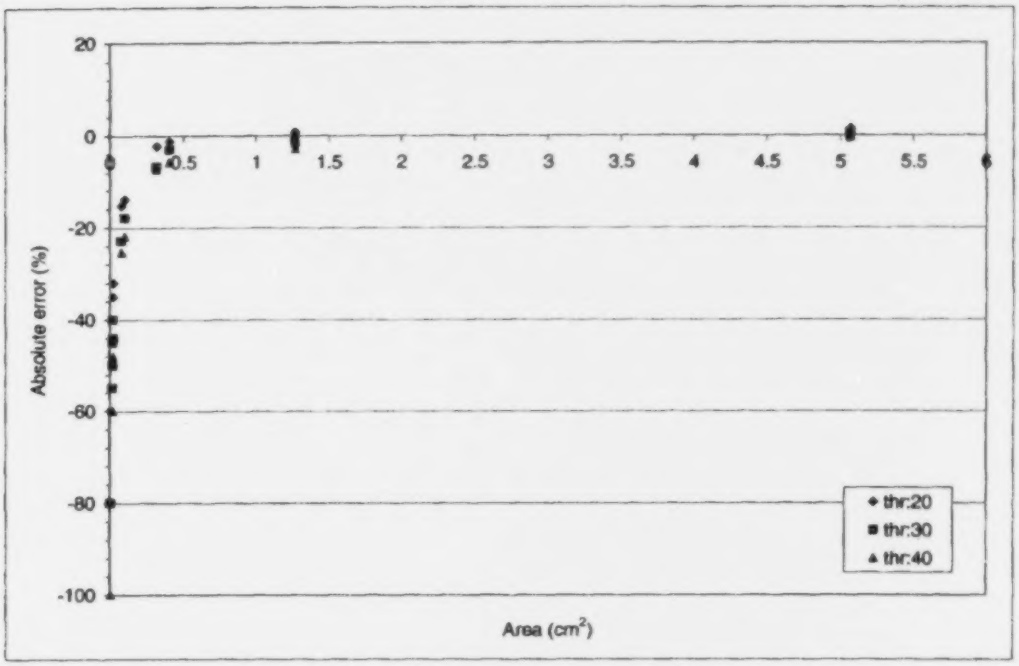

Figure 10. *Effect of the threshold value for circular holes from 1/32"Ø to 2"Ø*

4.2 Correction on Data Obtained After 1998

The correction derived in Section 4.1 cannot be applied to data obtained beyond 1998, since software modifications were completed on the hole area calculation [4]. A power law equation was applied to change the intensity of a pixel according to the current intensity level of that pixel.With the intensity correction factor applied to the area computation, the results are presented in Figure 11 for different threshold values. The LUT value has been set by default at 0.75 by the contractor. This value revealed the smallest error in area calculation. Figure 11 shows that as the accuracy for very small holes is increased by reducing the threshold value, the greater becomes the error for larger holes. Although the accuracy in hole area with the threshold set at 30 is significantly improved (between –40 % and +10 %) the threshold level still does not allow to distinguish the individual holes for the 5x5 grid of 1/16"Ø holes located at position (2,2) of Figure 1. The threshold needs to be higher to avoid the coalescence of

neighbouring small holes into one large hole. Figure 11 also shows that when the low intensity pixels are intensified, this is applied to all holes, that is small and large holes. Therefore, the error is now greater for the large holes.

To better represent the new curves of the absolute error for circular holes, a new equation is defined. Equation 4.3 is now used in combination with equation 4.2 to reduce the absolute error over the entire range of hole sizes:

$$f(x) = \frac{Ae^{-kx}}{x^C}(x - B) \tag{4. 3}$$

Constants A, B, C and k have to be defined through an iterative process. Once again, the constant C should be close to one. This last equation defines the best-fit curve for the data recorded after1998.

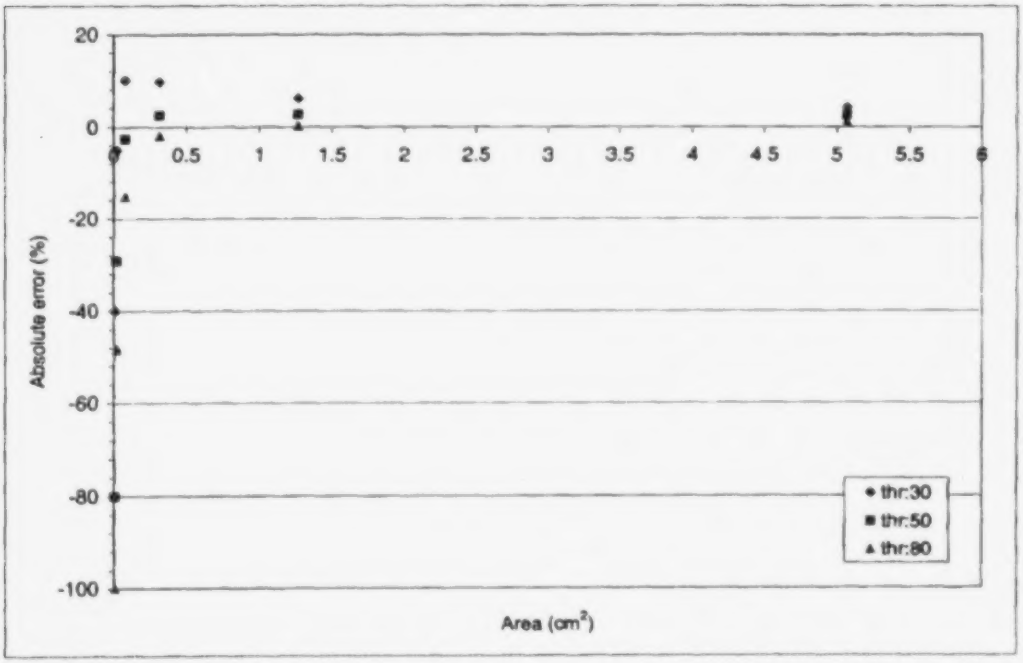

Figure 11. *Effect of the threshold value for circular holes from 1/32"Ø to 2"Ø using a LUT value of 0.75*

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5. Results and Discussion

The method described in the previous chapter, and initially used to reduce the absolute error in hole area computations, was developed for the data acquisition of witness plates using the WPAS. The results presented in this section are those representing the assessment of the hole area based on the calibration plate for the 2 ft x 2 ft light table.

An example of the correction which could be applied to data recorded prior to 1998 is shown in Figure 12. To obtain optimal results, the threshold was set to 30, and to cancel the effect of the power law equation used to correct the light intensity which was not yet applied to the system acquisition program, the LUT value was set to 1. These conditions allow the capture of all holes greater or equal to 1/32" in diameter. The individual holes of the grid in position (2,2) are only partially identified. The results after correction present an error which varies between +12 % and –13 %. The results show that the largest error is produced by the rectangular hole of 1.21cm^2 area since this hole is not close to the correction curve fit. One can also observe that the smallest holes have an error varying from –9 % to +12 %.

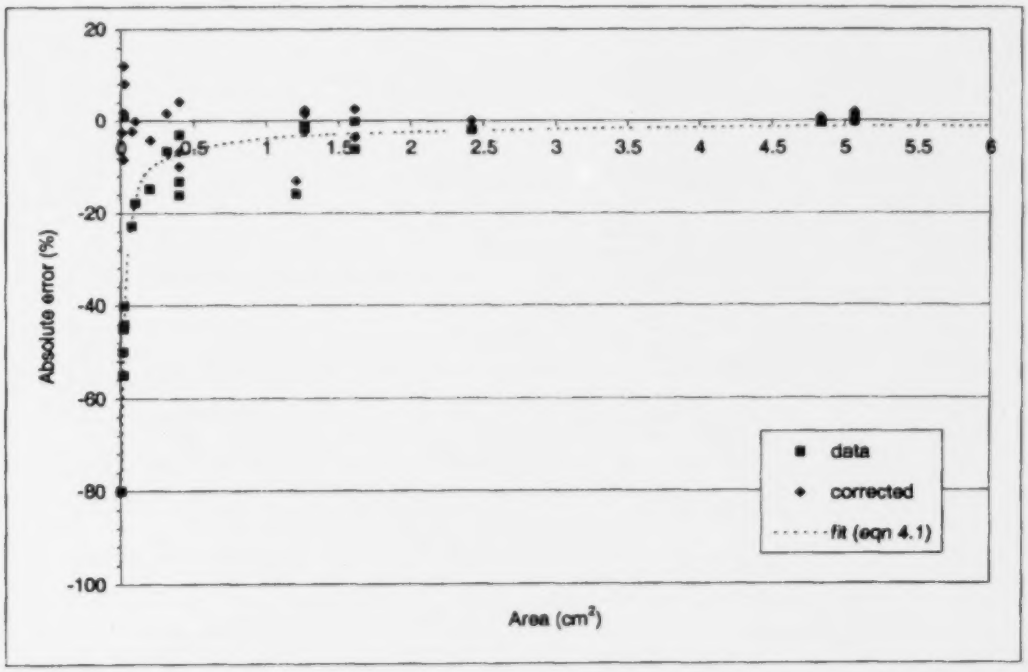

Figure 12. *Data of the absolute error (%) for the calibration plate with and without correction (the threshold value=30 and the LUT=1)*

Before applying the correction (i.e. equation 4.2) to the data obtained after 1998, it is important to define the optimum LUT and threshold values for maximum accuracy. To select the best intensity correction factor using the power law equation, a coefficient was created ranging from zero to one, that is, the LUT value. With the value equal to one, no correction is

made and the original intensity is kept. A decrease of this value results in the increase of the intensity correction level. Figure 13 presents the effect of the LUT coefficient on the hole area absolute error. Four different values of LUT were chosen. The threshold value 'thr' presented was optimised so that the smaller 1/32"Ø holes just begin to disappear (i.e. hole positions (2,3), (3,1), (5,2) and (6,1)). The value presented here resulted in the disappearance of no more than three 1/32"Ø holes for the entire 2 ft x 2 ft calibration plate. Threshold values of 30, 40, 55 and 60 were used with a corresponding LUT value of 1.00, 0.85, 0.75 and 0.65, respectively. The number of holes found on the calibration plate were 208, 214, 246 and 207, respectively. The maximum number of holes on the 2 ft x 2 ft calibration plate is 346 holes. Depending on the LUT value used, the 5x5 grid of 1/16"Ø holes located at position (2,2) in Figure 1 produced a different number of holes. The largest number of holes was obtained with LUT = 0.75, for which 246 holes were recorded.

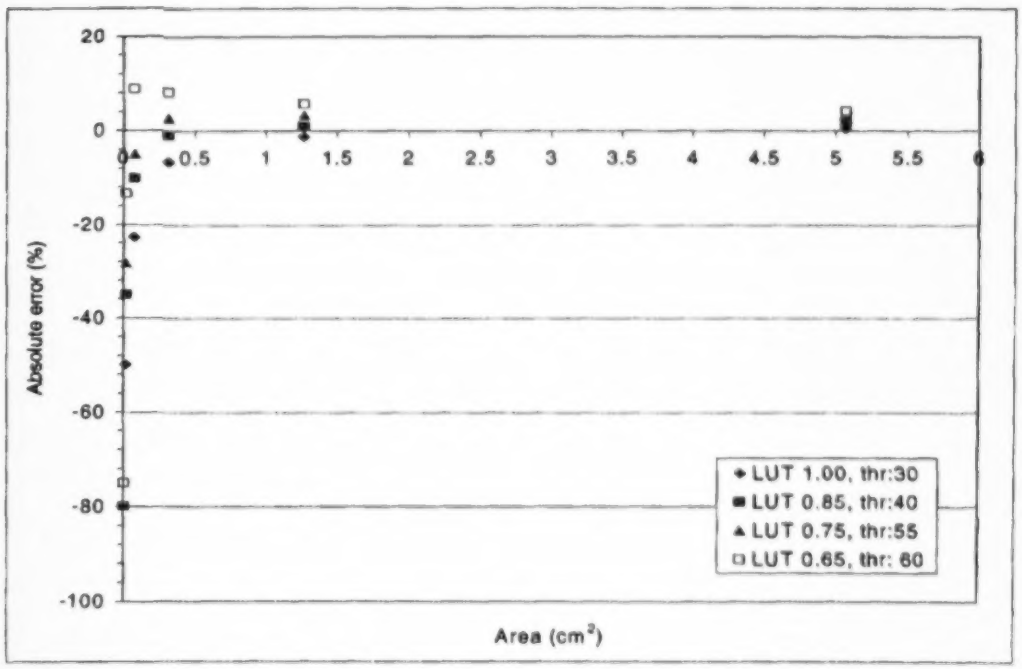

Figure 13. *Effect of the LUT value and of the threshold value for circular holes*

Figure 13 also reveals that, as the LUT value decreases and the 'thr' value increases, the absolute errors shift upwards. Additional information is obtained from Figures 14 to 17 where the areas are presented for each of the parameter settings combination of Figure 13 for circular and non-circular shaped holes. One can observe that holes of narrow rectangular shape, represented by the empty squares, have a hole area error which is more sensitive to the LUT value. A narrow rectangle 1/32" in width can be compared with a stack of 1/32"Ø holes. Therefore, as very small holes, they are affected significantly by the increase of light intensity. Also, the variation in the absolute error according to the shape of the holes is almost non-existent at LUT=0.75.

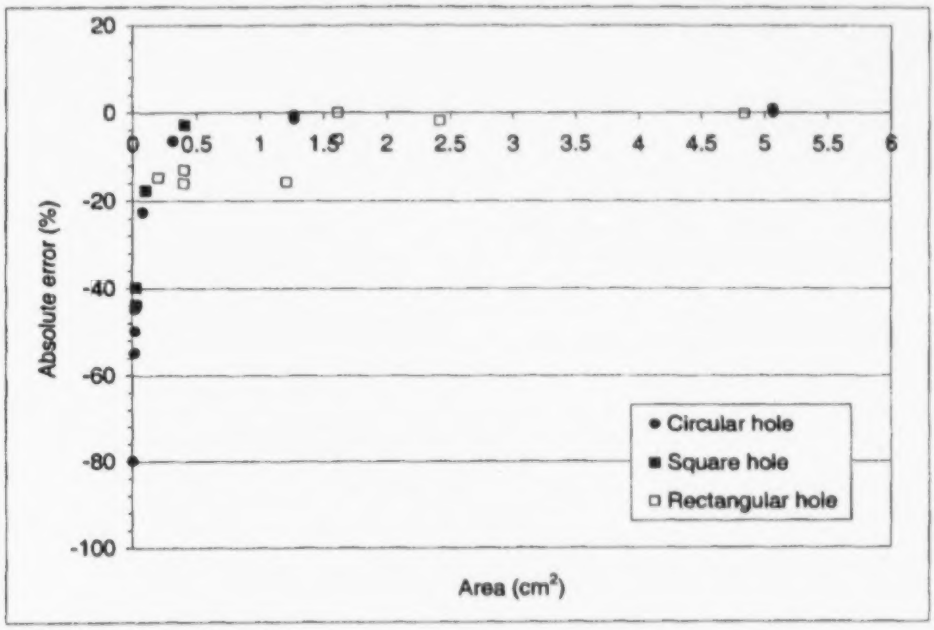

Figure 14. *Absolute error (%) for the calibration plate (LUT=1 and threshold=30)*

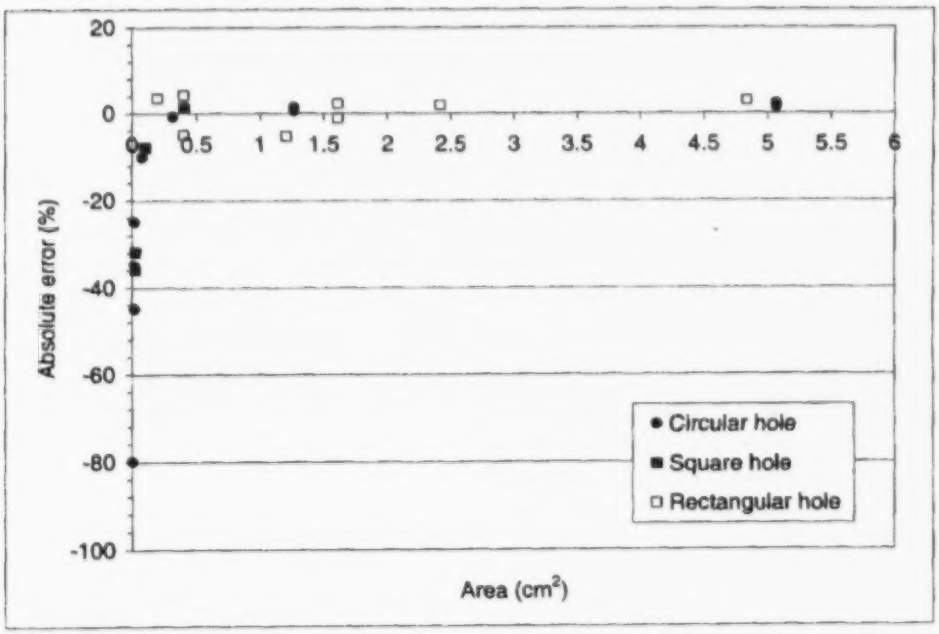

Figure 15. *Absolute error (%) for the calibration plate (LUT=0.85 and threshold=40)*

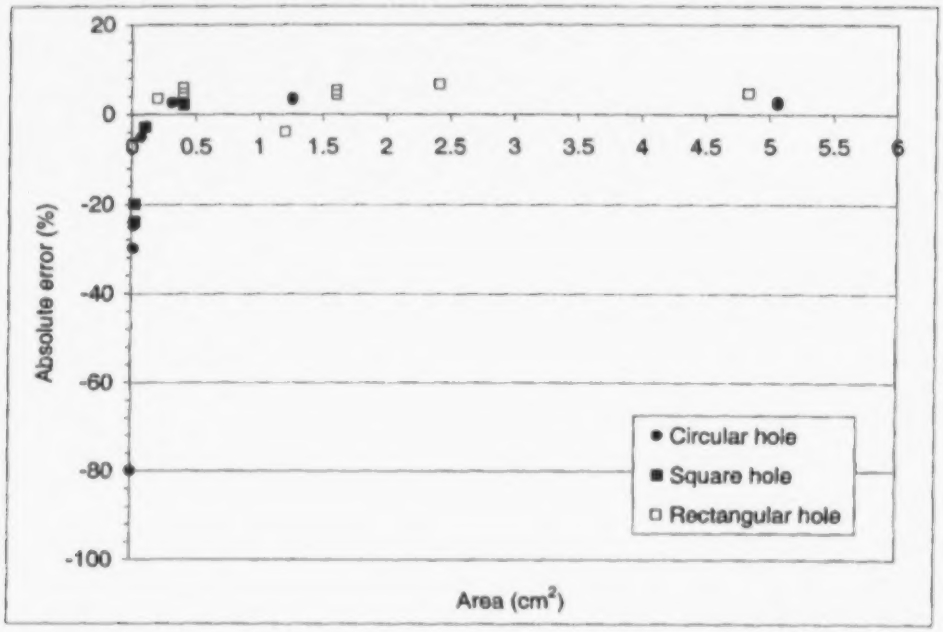

Figure 16. *Absolute error (%) for the calibration plate (LUT=0.75 and threshold=55)*

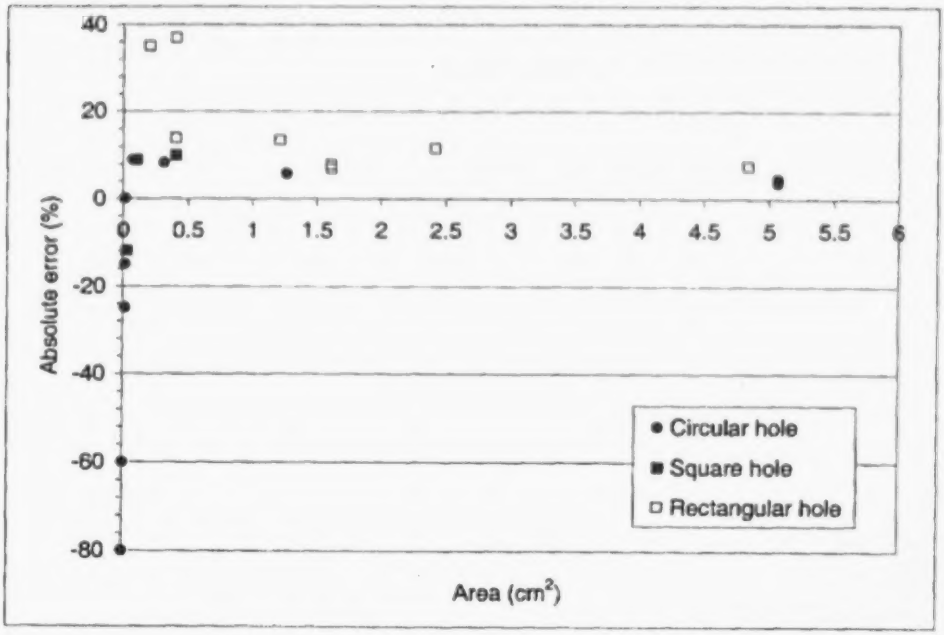

Figure 17. *Absolute error (%) for the calibration plate (LUT=0.65 and threshold=60)*

To correct the hole areas for plates analysed after 1998 at which time a correction was implemented to the calculations (i.e. LUT=0.75), the correction defined in equation 4.2 is applied with equation 4.3. Figure 18 shows a drastic improvement in the corrected hole area. The absolute error is below 5 % for all the data, except for the rectangular shaped hole of 1/16"x3" with a 1.21 cm^2 area (position (3,3)) where the error was 7.5 %. Here again, the data for hole areas superior to 6 cm^2 were not shown since the experimental data and the error were always beneath 2.5 %. This correction reveals an overall error below ±10 % for hole areas ranging for 0.005 to 20 cm^2.

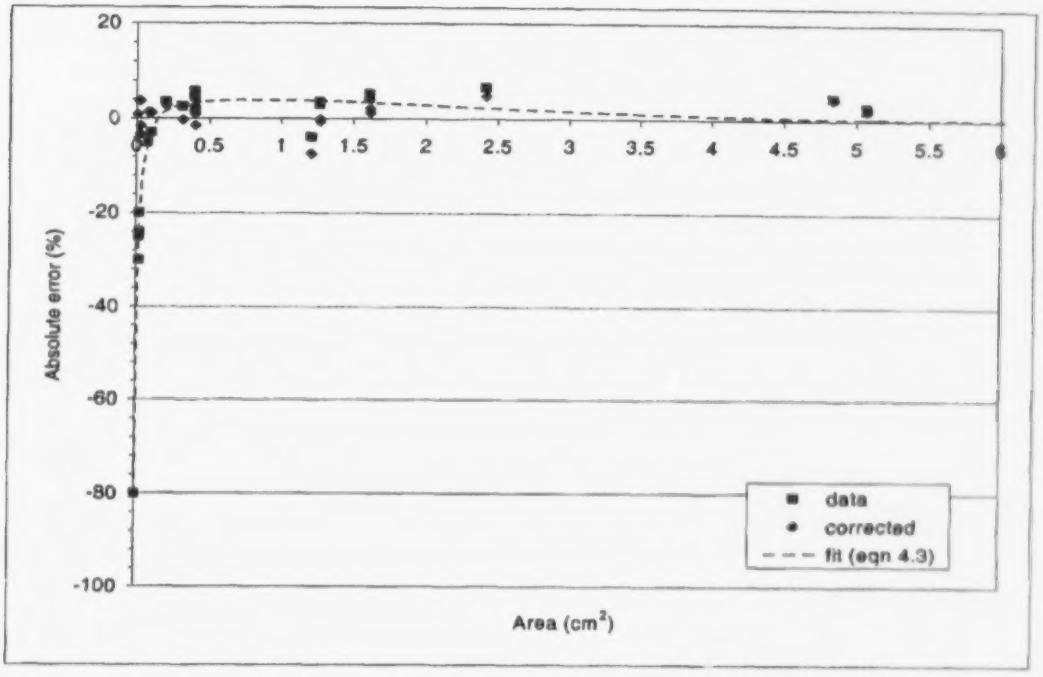

Figure 18. *Data of the absolute error (%) for the calibration plate with and without correction (threshold value=55 and the LUT=0.75)*

Since the previous results are all presented only for the 2 ft x 2 ft light table, a single correction will be applied for demonstration purposes, to the hole area for the 4 ft x 4 ft light table and corresponding calibration plate. In this case, the distance from the camera to the table is increased to 477 cm since the image to capture is larger. Figure 19 presents the absolute hole area error for a LUT value of 0.70 and threshold value of 40. Following a study completed by Imago Machine Vision Inc., it was found that the best results were obtained with those settings [2]. It is important to observe that no data is presented for the holes smaller than 1/16"Ø (0.02 cm^2) since the system does not detect these. The resulting correction generates an absolute error of ±10 %. This is indeed an improvement over the +15 % to −12 % error range obtained without a correction. It must be noted that here again the areas obtained from the 1/32"Ø and 1/16"Ø holes of the 5x5 grid were removed. The narrow rectangular hole having a 1/32" width was also removed since it was too thin to produce a good area assessment (it was confused with the background). The holes located at position (2,2) in Figure 1 produced just one large hole using this setting. The table being twice as big

as the 2 ft x 2 ft, the number of pixels for a specific hole was four times smaller. This can explain the disappearance of the 1/32″Ø holes.

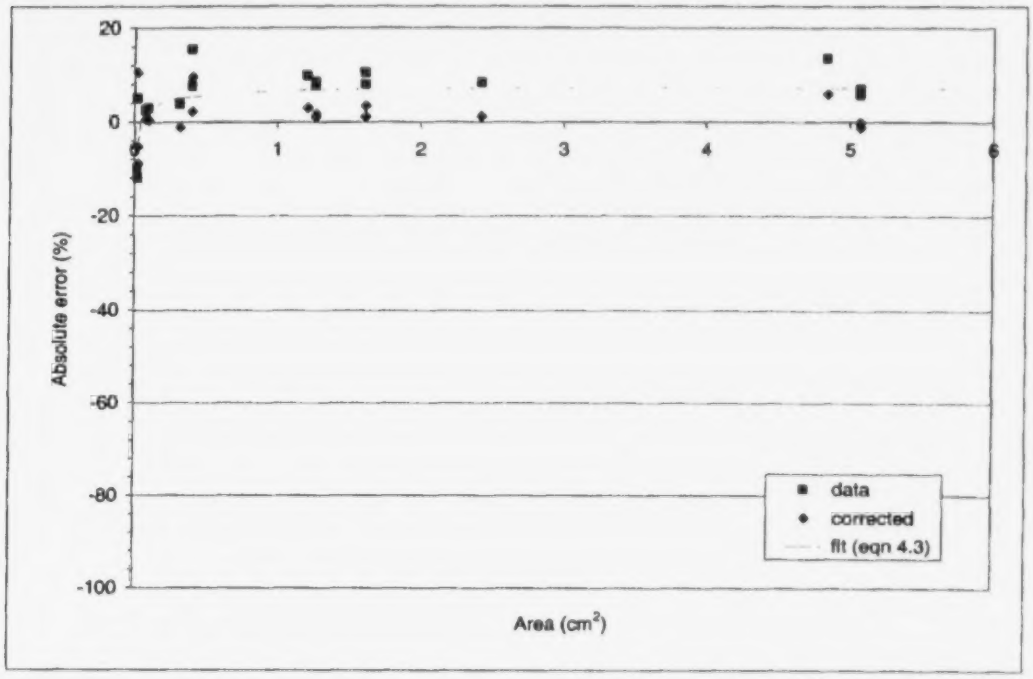

Figure 19. *Data of the absolute error (%) for the calibration plate with and without correction (threshold value=40 and the LUT=0.70)*

6. Conclusion

The method used to increase the hole area accuracy clearly shows improvements for the analysis of witness plates analysed prior to 1998. After 1998, improvements to software reduce the light intensity problem for small holes but only slightly increases the accuracy for holes ranging from 0.005 to 20 cm^2. However, if a correction is applied to the data, as done for data analysed prior to 1998, the improvement in the hole area calculations remains very interesting. The advantage of the correction skill is that even if a decision has been made to increase the threshold level to obtain information about a large number of holes confined in a really small area, the correction will still allow good results in hole area assessment.

The LUT and Threshold values should be set according to the hole geometry to study. If the holes are circular and larger than 0.5 cm^2 the LUT value could be set to one since no light intensity correction is needed. Depending on the holes to study, the parameters will have to be adjusted. This memorandum should help the WPAS user to better understand their effects.

Equations 4.1 and 4.3 were developed to improve the accuracy in hole area calculation for data obtained prior to 1998 and after 1998, respectively. For specific optimum conditions to scan plates, the accuracy in hole area assessment varies between +12 % and −13 % for plate analysed prior to 1998, after correction, the accuracy on hole area assessment is less than ±10 %.

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7. Recommendations

Additional work should allow a further increase in the hole area accuracy. It appears that progress will be limited by this system with the fluorescent light source and a 1024x1024 camera resolution. To improve the system, some change could be made but may require much work. For example, a laser source could be used to illuminate the table by a sweeping process to eliminate the light intensity problem observed with the diffusion of the present light source, but a complex new design of table and software would be required. Work could also be done to obtain a higher contrast between the black and white pixels but the camera wili need to support extremely bright areas. Also, the resolution of the camera could be increased to be able to see more holes from the 4 ft x 4 ft table and increase the accuracy. The camera currently used has 256 grey levels but up to 4096 grey levels can be obtained with newer cameras. The accuracy should be slightly improved since the area is evaluated with the grey level. Finally, the effect of the lens could be studied (but this effect is probably negligible) and similar work could be completed for the larger 4 ft x 4 ft light table.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
A	Constant (equations 4.1 and 4.3)
$Area_{computed}$	Area of holes computed by the WPAS
$Area_{corrected}$	Corrected hole area
$Area_{measured}$	Measured area of holes
B	Constant (equations 4.1 and 4.3)
BA	Behind-Armour
C	Constant (equations 4.1 and 4.3)
CE	Chemical Energy
DeCaM	Debris Characterisation and Modelling Software
DREV	Defence Research Establishment Valcartier
h	Height
k	Constant (equations 4.1 and 4.3)
KE	Kinetic Energy
LUT	Look-Up-Table
thr	Threshold value (grey intensity level)
w	Width
WPAS	Wit ess Pack Analysis System

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The witness packs used to characterise Behind-Armour (BA) Debris are of major concern for the defence research community. In order to quickly and efficiently analyse witness plates, the Defence Research Establishment Valcartier has been developing over the past few years the WPAS (Witness Pack Analysis System). The main work realised by this system consisted in the semi-automated computation of hole count, hole position and hole area assessment from witness plates. However, even with the high accuracy in hole area assessment obtained with a high resolution digital camera, important errors (up to 80%) appear for small or noncircular holes. This report presents a simple and efficient method to improve hole area assessment of witness plates. This method can be applied to correct the assessment of witness plates already analysed and for future analysis. The method consists in the definition of an equation to represent the absolute error based on the hole area, using calibration plate data and applying it to all witness plates. An error inferior to 10% is now obtained for all the holes ranging from 0.005 to 20 cm^2 in area.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Witness pack, hole area, camera, WPAS, calibration, kodak camera, light table, Behind-Armour Debris, Witness plate

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